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The contemporaneous tectonic events of the Indian Ocean and neighbouring areas

By A. *Pilger* and A. *Rösler*

Contents

Abstract

About 140 m. y. ago, the Indian Ocean opened and the Indian plate began drifting northward. With this event began the evolution of the tectonic and magmatic pattern of the present-day Indian Ocean and its related structures.

This paper deals with the temporal-tectonic coherences during the evolution of the Indian Ocean itself, of the Indian plate, the Himalayas, the Iran fold belt and the entire Afro-Arabian rift system. The authors themselves have worked in some of these areas and have also used and interpreted the voluminous and valuable literature concerning this region.

During the last 140 m. y., there have been various culminations of tectonic activity which affected contemporaneously the different areas or structures of the described region. 80 to 75 m. y. ago, corresponding with magnetic anomaly 32, there was a strong acceleration of the northward drifting Indian plate. At the same time, a culmination of ophiolitic eruptions (or an intensified sea floor spreading) occurred in the Tethys region, that is along the present-day Himalayas, Karakorum, Makran, Oman, Zagros Mountains and Taurides in southern Turkey. 70 to 53

m. y. ago, following the acceleration of the Indian plate, the Indian and the Arabian plates first made contact with Asia resulting in a strong folding in Iran and the first folding phase in parts of the Karakorum and Himalayas. It is significant that the two independently moving plates contacted Asia at the same time.

Intensified movements of plates combined with subduction of the continental crust of Arabia and India under Asia along the Indus suture line and the Zagros crush zone also occurred about 36, 25 and 10 m. y. ago and later. These movements corresponded with important orogenetic phases in the Himalayas and the Iran fold belt. At the same time, within the Red Sea and the Gulf of Aden an intensified sea floor spreading was in progress. The graben rifting of the East African Rift system also corresponded in time with these movements. The initial taphrogenetic phase occurred in the Afar rift 23 to 25 m. y. ago and in the Gregory Rift 10 m. y. ago Thus, different and independent structures around the Indian Ocean showed culminations of tectonic events at the same time.

The described region is extensive enough to obtain, by comparison of the varying structures, a first synopsis of temporal-tectonic activities showing how the earth's crust is influenced by contemporaneous tectonic events. Mainly, the contemporaneity of the tectonic events suggests a common origin of these dissimilar structures. Doubtless, the movements have their roots in the mantle or even in parts of the earth's core.

A preliminary comparison of the tectonic culminations in the described region with those in other parts of the earth show, in the sense of *Stille* (1924, 1940), approximately similar periods of tectonic culminations as, for example, east and west of the Atlantic Ocean. But, in regard to the ideas of the new global tectonics, it is too early to draw any conclusions from so distant and different structures and it would be premature to speak of a contemporaneity of the global tectonics.

I. Introduction

For interpreting the geological evolution of a structure, the temporal-tectonic coherences are just as important as the tectonic-mechanical connections or the relationships of the tectonic and magmatic activities.

First, changes or culminations in the intensity of tectonic movements as well as unconformities make it possible to subdivide the geological evolution of any described area into tectonic periods.

Second, many (but not all) important tectonic events, such as orogenetic or taphrogenetic phases, show a relatively abrupt development of strong tectonic movements which then diminish after a relatively short period of some 100,000 or a few million years. Thus, they are characterized by a strong and relatively short tectonic activity, which are clearly defined in time.

Third, important tectonic events, evidenced in upper parts of the crust, point to irregularities in the tectonic and magmatic activity in the mantle or even in deeper parts of the earth. Orogenetic or taphrogenetic phases, as well as anomalies which show changes of speed and direction of the sea floor spreading, surely have their roots in irregularities of the earth's interior.

Fourth, there is also the fact that many culminations of differing tectonic movements, as orogenetic or taphrogenetic phases, occurred contemporaneously in

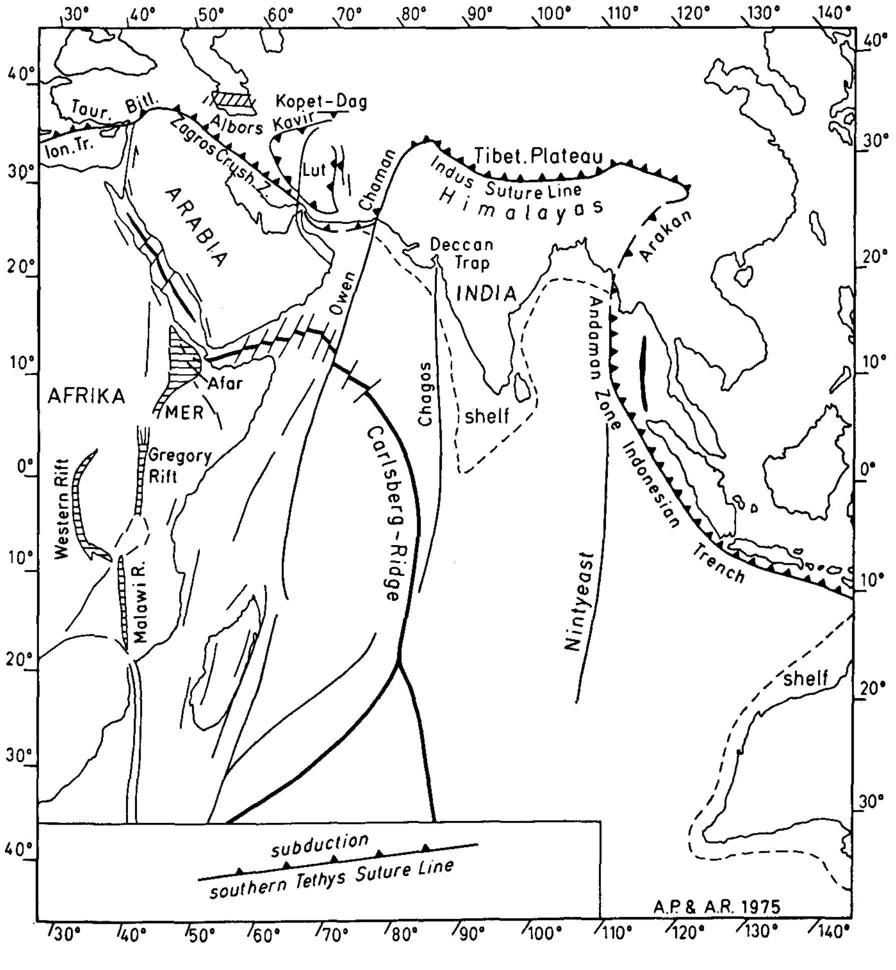

Fig. 1

Simplified sketch of the tectonic structures of the Indian Ocean and neighbouring areas. (From different authors; "Indus Suture Line" from *Stoneley* 1974, fig. 1.) "Southern Tethys Suture Line" = the tectonic line from the Ionian Trench in the west to the Indonesian Trench in the east. MER = Main Ethiopian Rift.

different regions. When such contemporaneous tectonic events cover extensive areas of the continental and oceanic crust, they point to a uniformity of the special processes in the deeper parts of the earth occurring during tectonic activity. These wide-spread tectonic culminations or tectonic phases make possible a division of the earth's evolution into tectonic periods. More than that, they reflect the mechanical and physico-chemical processes and the movements of possible convection streams within the earth's interior.

Very important scientific work by scientists from different countries has been carried out in respect to temporal-tectonic coherences. The contemporaneity of the orogenetic phases has been emphasized especially by *Stille* (1924, 1940, 1944). But, the hypothesis of plate tectonics and sea floor spreading has made relatively few contributions to the solution of these temporal questions (*Le Pichon* 1968, *Schneider* & *Vogt* 1968, *Heirtzler* et al. 1968, *Dewey* & *Horsfield* 1970, *Hallam* 1971, *Pilger* & *Rösler* 1974, 1976b, *Schwan* 1974, *Dewey* et al. 1973 and others). Therefore, it is necessary to collect further material concerning the temporal-tectonic coherences of the earth's evolution. For, we do not know the causes of the temporal relationships in the global tectonics and surely, these relationships throw new light on the mechanical and thermal coherences of the movements in the earth.

This paper is based on our original field research in some of the described areas and also on the study of the scientific literature concerning the tectonic and magmatic questions in the region between Africa, the Red Sea, Arabia, Iran, Himalayas, India and the Indian Ocean. The Indian Ocean and its surroundings are a section of the crust which shows clear tectonic connections of evolution. There will also be temporal-tectonic coherences which would generally complete our knowledges of the mechanical and physico-chemical coherences within the interior of the earth.

II. Temporal-tectonic events within the Indian Ocean and its northern and western neighbouring areas

1. Indian Ocean and Indian plate

In the late sixties the theory of plate tectonics and sea floor spreading was applied to the Indian Ocean (*Udintsev* 1966, *Le Pichon* 1968, *Le Pichon* & *Heirtzler* 1968, *Heirtzler* et al. 1968, *Dietz* & *Holden* 1970 and others). Following the hypothesis of *Vine* & *Matthews* (1963), the geomagnetic absolute time scale, based on linear magnetic anomalies, could also be extended to the Indian Ocean (*Heirtzler* et al. 1968). The oldest anomaly which can be defined is No. 32 and dates at about 77.5 m. y. ago (*Heirtzler* et al. 1968, *McKenzie* & *Sclater* 1971). This date corresponds with the Campanian in Upper Cretaceous time. It is generally assumed that the Indian Ocean opened even before this time but the proof of this can only be gathered from the polar wandering and paleomagnetic

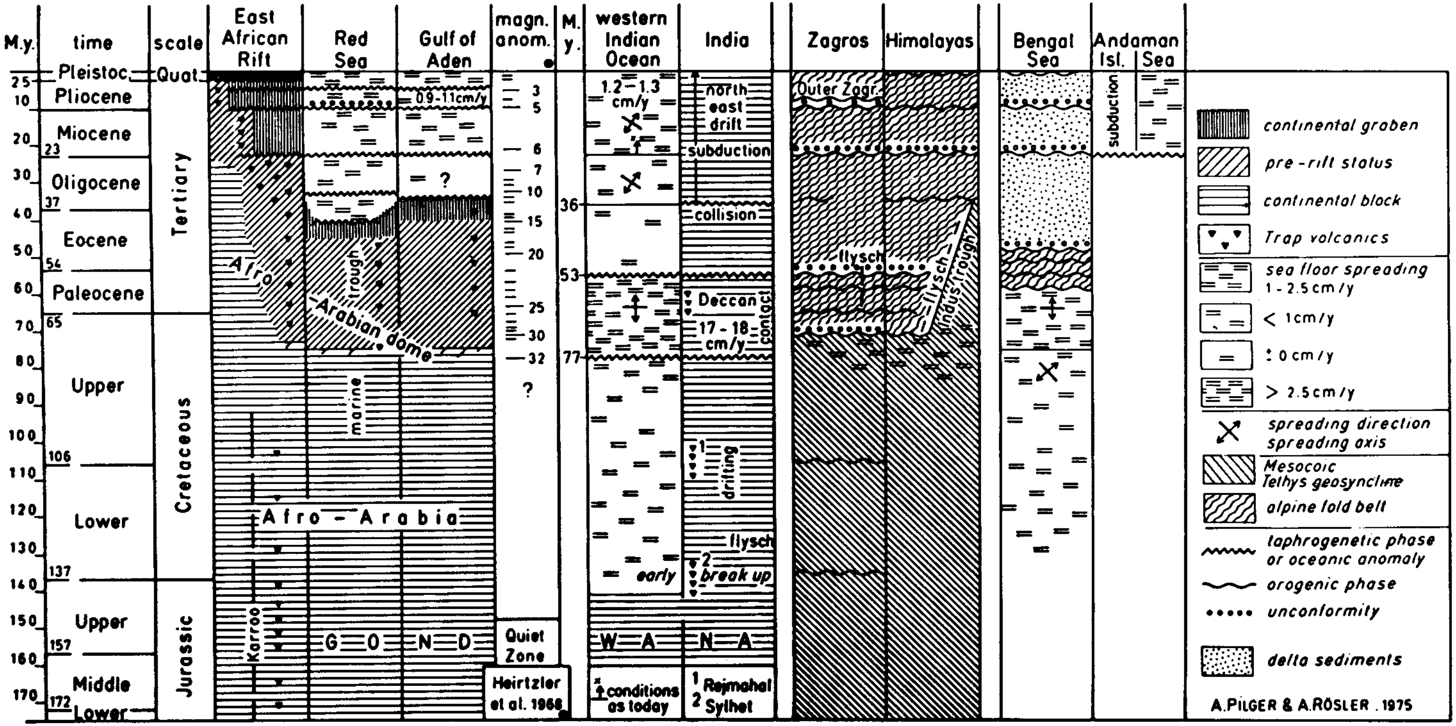

Fig. 2

Synopsis of the geologic-tectonic evolution of the Indian Ocean and neighbouring areas.

and geological conclusions of the Gondwana continent (see *Smith* & *Hallam* 1970, *McElhinny* 1970, *McElhinny* & *Luck* 1970, *Laughton* et al. 1972, 1973 and others). *Dietz* & *Holden* (1970) suggested an opening of the Indian Ocean and a loosening of India from Africa in Triassic time. First faults, lineaments and also marine basins, for instance west of Madagascar, can surely be dated back to Permo-Triassic and Jurassic time (*Creer* 1965, 1968 and others). But the real opening of the Indian Ocean or the separation of India from Africa and the still combined continent of Australia/Antarctica began probably on the Jurassic-Cretaceous boundary, or in the lowest part of the Cretaceous about 140 m. y. ago (*King* 1962, *Le Pichon* 1968, *Le Pichon* & *Heirtzler* 1968, *McElhinny* 1970, *Fisher* et al. 1971, *Curray* & *Moore* 1974 and others).

Combined with the opening of the Indian Ocean, a faulting and rifting occurred in Gondwana, especially in southeastern Africa. It was accompanied by an alkaline and peralkaline volcanism of mainly basaltic type. There were two periods of volcanism during Mesozoic (*Sowerbutts* 1972). The older suggests a first faulting during the Triassic and Jurassic. The second and most important occurred with the Karroo basalts on the boundary between the Jurassic and the Cretaceous. Contemporaneous trap eruptions occurred on the Indian plate with the Sylhet basalts on the Jurassic-Cretaceous boundary and the Raymahal basalts 105 to 100 m. y. ago (*Athavale* et al. 1963, *Wensink* 1973). A first flysch sedimentation also began all around the Indian plate (*Gansser* 1964, see fig. 4 of *Curray* & *Moore* 1974).

The evolution of the Indian Ocean during Cretaceous time is less clear (*McKenzie* & *Sclater* 1971). The spreading started slowly and was probably obliquely directed, compared to the later movements during Tertiary time (*Le Pichon* & *Heirtzler* 1968, *McKenzie* & *Sclater* 1971, *Sclater* & *Harrison* 1971, *Curray* & *Moore* 1971, 1974). However beginning with anomaly 32, which dates about to 77.5 m. y. ago or to uppermost Cretaceous, the history of the Indian Ocean can clearly be reconstructed. A strong acceleration in spreading began with anomaly 32. There was an E–W directed spreading axis and a northward directed rapid drifting of the Indian plate which amounted to 17–18 cm/y. (*McKenzie* & *Sclater* 1971, *Sclater* & *Harrison* 1971, *Curray* & *Moore* 1971, 1974, *Fisher* et al. 1971, *Wensink* 1973, *Laughton* et al. 1972, 1973). The period of very rapid sea floor spreading within the Indian Ocean and the rapid northward drifting of India continued until about 56 or 53 m. y. ago (anomaly 23 to 21) (*McKenzie* & *Sclater* 1971, *Laughton* et al. 1972, 1973, *Curray* & *Moore* 1974, *Sclater* & *Fisher* 1974, *Johnson* et al. 1976).

Therefore, the period of a very strong sea floor spreading and drifting within the Indian Ocean continued for about 22 to 24 m. y. which covers Upper Campanian, Maastrichtian, Paleocene and the lowest part of Lower Eocene. During the Paleocene, the Deccan Trap also was erupted on the western side of the drifting Indian plate (*Wellman* & *McElhinny* 1970, *Wensink* 1973 and others). There are early Tertiary and late Cretaceous unconformities in the Indian Ocean sediments found by the Deep Sea Drilling Project (DSDP) (*Pimm* & *Sclater* 1974, *Davies* et al. 1975). In the area of the present Bay of Bengal, the time of 55 m. y. ago corresponds with an intensive regional unconformity in the sedimentary section underlying the Tertiary delta sediments (*Curray* & *Moore* 1971, 1974). Further to the southeast, late Cretaceous and early Tertiary subduction zones are exposed in several areas of the western half of Java (*Hamilton* 1973).

The period following the anomaly 21 from 56 or 53 m. y. ago until the anomaly 12 from 36 or 35 m. y. ago (in the southwestern Indian Ocean until 20 m. y. ago) showed an abrupt deceleration of spreading and plate motion with even intermittent periods with no spreading in the entire region of the Indian Ocean (*McKenzie* & *Sclater* 1971, *Fisher* et al. 1971, *Laughton* et al. 1972, 1973, *Curray* & *Moore* 1974, *Sclater* & *Fisher* 1974). Since early Oligocene or anomaly 12, the spreading again accelerated slightly and changed to a different direction with a NW-SE spreading axis. Therefore, the Indian plate began to drift more northeastward or north-northeastward (*McKenzie* & *Sclater* 1971, *Fisher* et al. 1971, *Sclater* & *Fisher* 1974, *Curray* & *Moore* 1974, *Molnar* & *Tapponnier* 1975). Unconformities in the Oligocene sediments corresponding with these tectonic events were found by drilling (*Pimm* & *Sclater* 1974, *Davies* et al. 1975).

With the beginning of Miocene, 23 m. y. ago, or with anomaly 6, the spreading rate has been constant in the entire Indian Ocean until today. There has been a spreading amount of 1.3 to 1.2 cm/y. in the northwestern Indian Ocean, but of 2 to 3 cm/y. in its southern parts (*Le Pichon* & *Heirtzler* 1968). Furthermore, from the Miocene onward, the sedimentation facies and paleoenvironment in the Arabian Sea, west of India, was not too much different from the situation at present time (*Closs* et al. 1974).

The northward and northeastward drifting of the Indian plate led to its collision with Asia. In this regard, *Dewey* & *Bird* (1970) have developed their ideas of the type of orogeny caused by the collision of two continents, which is especially applicable to the genesis of the Himalayas. In accordance with the hypothesis of sea floor spreading and plate tectonics, the drifting Indian plate was about 150 km thick and consisted of the sialic Indian continental crust and part of the Indian Ocean crust, together with part of the underlying upper mantle. So, first to contact with Asia was the oceanic crust and/or parts of the mantle north of the Indian continent with all the tectonic and magmatic consequences, such as the first subduction of the oceanic crust under Asia, with a trench, a volcanic island arc and ophiolitic eruptions within the Tethys geosyncline. It must be assumed that this process began during the Campanian and continued during the Maastrichtian and Paleocene (*Gansser* 1964, 1966, *Stoneley* 1974 and others), (fig. 2).

Later, the Indian (sialic) continent made contact with Asia. This was the real collision of two continental blocks in the sense of *Dewey* & *Bird* (1970). At the same time, the subduction of the (sialic) Indian block under Asia began. These tectonic events must be dated on the Paleocene-Eocene boundary, about 56 or 53 m. y. ago (*Powell* & *Conaghan* 1975), and/or on the Eocene-Oligocene boundary, about 36 m. y. ago (*Molnar* & *Tapponnier* 1975). These two culminations of contact and subduction occurred together with strong orogenetic folding in the Himalayas (see the next chapter).

Thus, contact, collision and subduction of the Indian plate and Asia reflected by the folding of the Tethys deposits and the tectonic forming of the Himalayas by orogenetic phases.

The main tectonic events in the evolution of the Indian Ocean are summarized in the table below.

Table 1 (Cf. fig. 2)

Age m. y.	Magnetic anomaly	Event
25–23	6	Second push of collision and strong subduction, beginning of sea floor spreading and subduction in the Andaman Sea
~ 36	12	Collision of the continental part of the Indian plate with Asia and subduction under the Tibetan plateau, change of drift direction
53	22	End of the accelerated drifting
77–53		First contact of the oceanic crust of the Indian plate with Asia
77.5	32	Beginning of strong acceleration of the drifting of the Indian plate
140		Birth of the Indian Ocean, start of northward drift of the Indian plate

2. The Himalayas

The Himalayas of today emerged from the former Mesozoic Tethys geosyncline. This geosyncline has been compressed by the collision of the Indian plate with Asia since the beginning of Tertiary (*Gansser* 1964, 1966, *Dietz* & *Holden* 1970 and others), and during this compression the Tethys geosyncline disappeared and the Himalayas were folded. A remainder basin, the Indus trough, existed until late Eocene (*Stoneley* 1974). The first morphological Himalayas came into being not earlier than late Miocene (*Gansser* 1964, *Wadia* 1967, *Stoneley* 1974).

The so-called Indus suture line (*Gansser* 1964) points to the contact where the Indian plate dips under Asia doubling the thickness of the continental crust in the Tibetan plateau (*Desio* & *Marussi* 1966, *Gupta* & *Narain* 1967). The Indus suture line runs E–W along the Indus and Brahmaputra valleys (*Gansser* 1964, 1966), (see fig. 1). It continues to the western edge of India, then turns southward into Kashmir, runs through Afghanistan and Pakistan and enters the Indian Ocean off Makran (*Gansser* 1964, 1966, *Wadia* 1967, *Stoneley* 1974). On the eastern edge of

India, the Indus suture line follows the Brahmaputra valley running southward and continuing into the Indonesian trench. A chain of lenses of coloured melange along the Indus suture line with ophiolites, glaucophanitic shistes, radiolarites, flysch and geosynclinal sediments indicates the former Tethys geosyncline.

No folding occurred during Mesozoic time before the Maastrichtian in the region of the Himalayas or on the northwestern, northern or northeastern border of the Indian plate. All structures are the result of plate movements during Tertiary and Quaternary (*Gansser* 1964, 1966, *Wadia* 1967, *Dietz* & *Holden* 1970 and others). The first folding of the Himalayas, the Karakorum orogeny, occurred on the northwestern edge in the Maastrichtian and Paleocene (*Valdiya* 1964a, 1964b, *Gansser* 1964, 1966, *Athavale* 1973, *Stoneley* 1974). Possibly, there also were tectonic movements in other parts of the Himalayan region.

It must be assumed, that the first folding phase corresponded to the first contact of the Indian plate (probably its oceanic crust) with Asia. The contact is proved by the early Tertiary flysch in the Himalayas which contains granitic detritus which must have come from Asia, and not from India (*Gansser* 1966, *Stoneley* 1974). The tectonic movements in the Himalayas before the lowest Eocene coincide approximately with a regional unconformity, formed 55 m. y. ago, in the sediments underlying the present Bay of Bengal (*Curray* & *Moore* 1974), (fig. 2).

The next orogenetic phase in the Himalayan region, the post-Kirthar orogeny, occurred on the Eocene-Oligocene boundary (*Athavale* 1973, *Le Fort* 1975, *Kennett* & *Watkins* 1976). The contact of the Indian plate and Asia, the real collision of the sialic parts of the two plates, resulted in a culmination of the compression. It began abruptly and ended during Oligocene time. Intensive subduction took place where continental India was pushed under the Tibetan plateau during the collision.

The most important orogenetic phase with strong folding, thrusting and granitisation in the entire Himalayan region and with strong subduction of the Indian plate under the Tibetan plateau occurred at the beginning of the Miocene and continued probably into the Middle Miocene (*Valdiya* 1964a, 1964b, *Gansser* 1964, 1966, *Wadia* 1967, *Athavale* 1973, *Stoneley* 1974, *Le Fort* 1975). On the Oligocene-Miocene boundary, sea floor spreading also started in the Andaman Sea along with the subduction in the area of the Andaman Isles and is still continuing today (*Curray* & *Moore* 1974). On the Miocene-Pliocene boundary, about 10 m. y. ago, a further orogenetic event took place in the Himalayas and in Pakistan (*Valdiya* 1964a, 1964b, *Gansser* 1964, 1966, *Wadia* 1967, *Athavale* 1973, *Stoneley* 1974, *Le Fort* 1975). It corresponds to an important unconformity in late Miocene within the 12 km thick delta sediments of the Bengal Sea (*Curray* & *Moore* 1971).

The last orogenetic movements of the Himalayan region occurred only in its outer parts. They began at the end of the Pliocene and were strongly active in the Pleistocene. They are still continuing today as a result of the continuing movement of the Indian plate against and under Asia.

Summarizing the culminations in the tectonic evolution of the Himalayas, the following data can be recognized:

Table 2 (Cf. fig. 2)

Age m. y.	Magnetic anomaly	Geological time	Tectonic culmination
10 and later			Folding of the outer parts of the Himalayas
23	6–7	Oligocene-Miocene boundary	Third and main folding phase, unconformity in the Bengal Sea
40–37	12	Eocene-Oligocene boundary	Second folding phase
70–53	30–22	Lowest Eocene, Paleocene and Upper Maastrichtian	First folding phase in the Karakorum, and probably in other parts of the Himalayas, flysch
77–70	32–30	Lower Maastrichtian and Campanian	Tethys geosyncline, ophiolites, sea floor spreading, trench, island arc, subduction, glaucophanitic shistes

3. Jordan-Dead Sea-Wadi Araba Rift, Red Sea, Gulf of Aden

The Jordan-Dead Sea-Wadi Araba Rift forms the northernmost part of the 6,000 km long Afro-Arabian rift system. It continues southward, into the Red Sea and the Gulf of Aden. In the late Cretaceous and on the Cretaceous-Tertiary boundary, the Red Sea region was a part of the upwelling Afro-Arabian dome. A first faulting and rifting began together with first Trap eruptions, around the Gulf of Aqaba and the Gulf of Suez (*Said* 1962, *Abdel-Gawad* 1970). In Yemen, Trap basalt eruptions are intercalated into Upper Cretaceous sediments (*Geukens* 1966). The stable connection between Africa and Arabia began to desintegrate. At the end of the Eocene, the upwelling of the Afro-Arabian dome came to another culmination together with a stronger fracturing of the proto-Red Sea (*Mohr* 1967, *Gass* 1970a, 1970b, 1975).

In the Dead Sea-Wadi Araba Rift, Upper Eocene conglomerates indicate taphrogenetic movements (*Bender* 1968a, 1968b). An intensive fracturing took place in the region of the Red Sea and Gulf of Suez (*Said* 1962, *Abdel-Gawad* 1970, *Gass* 1970a, 1970b). *Girdler* & *Styles* (1974a, 1974b, 1976) have shown that a first oceanic rifting with sea floor spreading took place in the Red Sea region between 41 and 34 m. y. ago. The tectonic activity in the region of the Gulf of Aden also began on the boundary between the Eocene and Oligocene and continued through the Oligocene with only minor fracturing at first (*Azzaroli* 1968). In contrast, *Garson* & *Krs* (1976) have suggested tectonic movements along the Gulf of Aden area since the Upper Cretaceous.

With the end of Oligocene or the beginning of Miocene, 23 to 25 m. y. ago, a stronger rifting, combined with a basaltic volcanism began in the regions of the Red Sea and the Gulf of Aden (*Laughton* 1966a, 1966b, *Girdler* 1965, 1968, *Illies* 1965, 1970, *Azzaroli* 1968, *Brown* 1970 and others). The Red Sea depression could have attained the approximate form of an intercontinental graben (*Sestini* 1965, *Whiteman* 1968, *Illies* 1965, 1970). With the Miocene, a marine transgression intruded from the Indian Ocean into the Gulf of Aden, but without invading the Red Sea area (*Beydoun* 1970), and the Carlsberg Ridge began to penetrate into the Gulf of Aden as the Sheba Ridge (*Matthews* 1966, *Heezen* & *Ewing* 1963). It is quite probable that an oceanic crust began to develop in the Gulf of Aden in the early Miocene (*Laughton* 1966a, 1966b, *Laughton* et al. 1970, *Beydoun* 1964) although the magnetic anomalies in the Gulf of Aden can only be traced as far back as anomaly 5 (= approx. 10 m. y. ago) (*Laughton* et al. 1970).

Stronger crustal movements began on the Miocene-Pliocene boundary. The Red Sea separated from the Mediterranean (*Swartz* & *Arden* 1960), but opened on the southeast trough the Gulf of Aden into the Indian Ocean, forming the Straits of Bab el Mandeb. An unconformity between the Upper Miocene and the marine oozes of the Pliocene resulted from westward transgression of the Indian Ocean (*Coleman* 1974). At the end of Pliocene, the oceanic Sheba Ridge entered the Gulf of Tadjura and parts of the northern Afar (*Barberi, Tazieff* & *Varet* 1972, *Barberi, Borsi* et al. 1972, *Harrison* et al. 1975 and others).

Summarizing the facts of the tectonic evolution of the Jordan-Dead Sea-Wadi Araba Rift, Red Sea and Gulf of Aden, the following data can be recognized:

Table 3 (Cf. fig. 2)

Age m. y.	Geological time	Event
10	Miocene-Pliocene boundary	Strong faulting movements and sea floor spreading in the Red Sea and Gulf of Aden
23	Oligocene-Miocene boundary	Beginning of sea floor spreading in the Gulf of Aden
41		Beginning of sea floor spreading in the Red Sea
	Cretaceous-Tertiary boundary	Uplifting, beginning of faulting with Trap eruptions

4. East African Rift System

The East African Rift system is the southern part of the Afro-Arabian rift system and the southern continuation of the Red Sea and the Gulf of Aden. It begins in the north with the Afar depression, which forms a triple junction with the Red Sea and the Gulf of Aden. The Afar depression continues directly southward

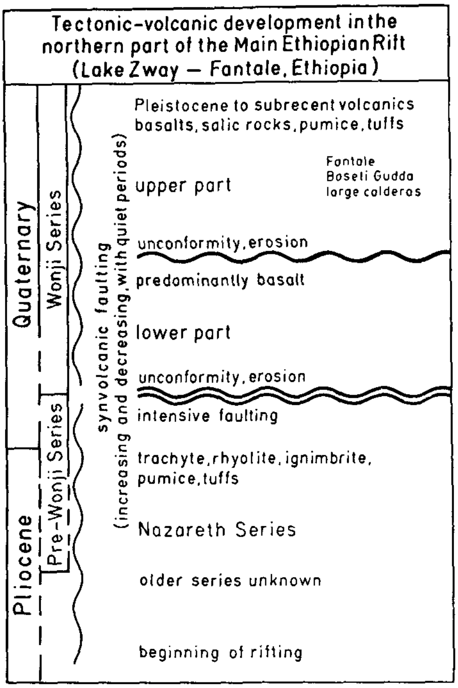

Fig. 3
Typical taphrogenetic phase in the northern part of the Main Ethiopian Rift, East African Rift system. The taphrogenetic phase is characterized by an unconformity, a changing in the geochemistry of the volcanic rocks, a changing in the tectonic directions and a relatively short duration. (From *Pilger* & *Rösler* 1974, fig. 2.)

into the Main Ethiopian Rift which ends in Kenya. Here, the Gregory Rift begins as a part of the Eastern Rift which is situated east of Lake Victoria and extends from Kenya through Tanzania to Mozambique. West of Lake Victoria, the Western Rift runs southward from Uganda through Lake Tanganyka to Malawi.

The entire rift system is a significant area of continental rifting with extension and graben fracturing and all the tectonic and volcanic consequences. Generaly, the pre-rift status before the rifting is characterized by slowly increasing fracturing of mainly local and minor significance (*Pilger* & *Rösler* 1974, 1976b). An associated alkali volcanism, called the Trap volcanism, reached a thickness of 2,000 to 3,000 m in Ethiopia and Yemen. In northern Afar, it has an early Tertiary age. In the southern Afar, the Trap Series and the pre-rift status are younger and comprise the Miocene (*Juch* 1975, *Kunz* et al. 1975, *Morbidelli* et al. 1975), (fig. 4).

In all parts of the East African Rift system, the real graben fracturing began relatively rapidly with an initial taphrogenetic phase. This is characterized by a

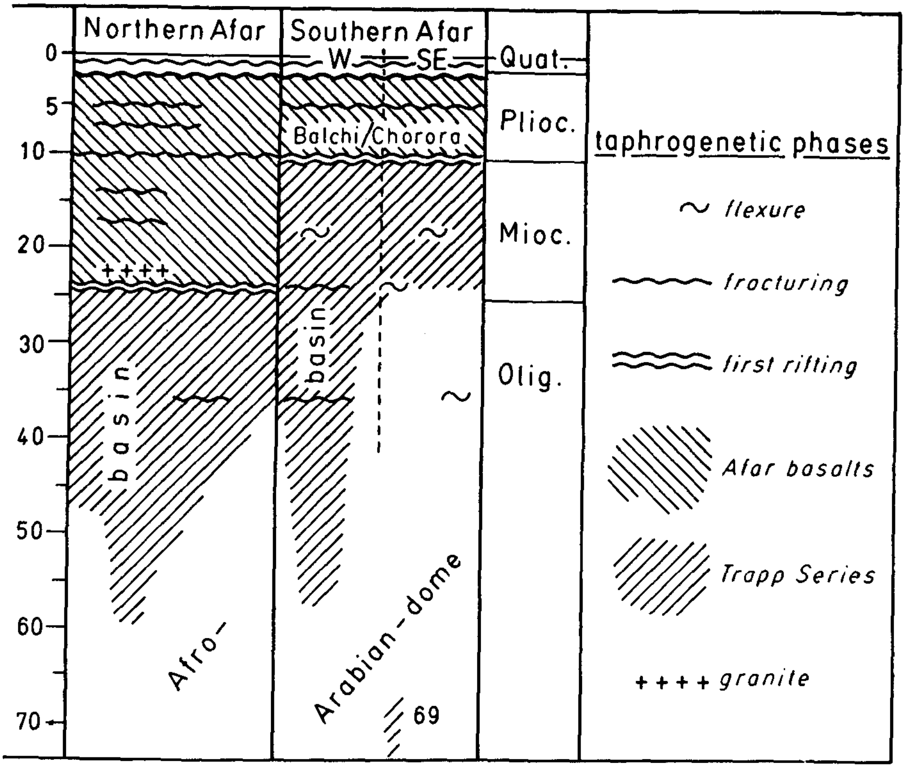

Fig. 4
The volcanic-tectonic evolution in the northern and southern Afar, Ethiopia. The initial phase of the real graben rifting (= "first rifting") began abruptly and is older in the north. "Basin" means the "Afar Trap Basin" with 2,000 to 3,000 m of alkaline basalts and related volcanic rocks.

climax of volcanic activity, a change in the geochemistry of the volcanic rocks and an unconformity of the graben sediments and volcanics above older deposits which had previously been tilted and eroded (e. g. in the Afar: *Tazieff* & *Varet* 1969, *Tazieff, Varet* et al. 1972, *Brinckmann* & *Kürsten* 1971, *Barberi, Borsi* et al. 1972 and others).

The beginning of the real graben rifting, with all its tectonic and volcanic features, is of practically the same type in all regions of the East African Rift system. But the timing of the onset shows some pecularities.

In the northern Afar, the graben rifting began 23 to 25 m. y. ago at the boundary of the Oligocene and Miocene (*Bannert* et al. 1970, *Barberi, Borsi* et al. 1970, *Brinckmann* & *Kürsten* 1971, *Barberi, Tazieff* & *Varet* 1972 and others). In the southern Afar and on its southeastern escarpment, the initial phase started at the end of the Miocene, 11 to 9 m. y. ago (Afar-Arbeitsgemeinschaft 1974, *Christiansen* et al. 1975, *Juch* 1975, *Kunz* et al. 1975). In the Gregory Rift, in Kenya, the initial phase occurred at the Miocene-Pliocene boundary, about 10 m. y. ago (*McCall* 1967, *McCall* et al. 1967, *Girdler* et al. 1969, *Baker* 1970, *Picard* 1970, *Baker* & *Wohlenberg* 1971, *Logatchev* et al. 1972, *Baker, Mohr* & *Williams* 1972). On the Western Rift, and on the Eastern Rift south of Kenya, the initial phase occurred not earlier than 2 m. y. ago (*Davies* 1956, *King* & *Sutherland* 1966, *Logatchev* et al. 1972, *Logatchev* 1976, *Beloussov* et al. 1974). From the above, it is evident that the evolution of the entire East African Rift system shows a clear temporal-tectonic progression from north to south (*Pilger* & *Rösler* 1975b, 1976b). It continued in stages advancing from the northern to the southern parts of the East African Rift system.

But, this temporal-tectonic progression of the rifting from north to south does not indicate that the tectonic activity in the northern (earlier fractured) regions had ended when the rifting in the southward situated regions began. Generally, the rifting was occurring in all parts of the entire rift, from the time of local onset to the present with increasing and decreasing tectonic and volcanic activities and culminations. In other words, the initial phases of the southern and younger parts of the entire rift system correspond with a tectonic and volcanic rejuvenation of the earlier fractured parts in the north. Furthermore, all taphrogenetic phases in the different parts of the East African Rift system occurred contemporaneously with synchronous culminations of the tectonic activity. For instance, the initial phase of the Gregory Rift, about 10 m. y. ago, corresponds with a renewed strong taphrogenetic phase in the Afar. The initial phase in Tanzania at the end of the Pliocene closely corresponds with younger taphrogenetic activities in the Gregory Rift and in the Afar and is generally characterized by a rift-in-rift structure. During these same periods, strong oceanic activity also occurred in the Red Sea and the Gulf of Aden.

So, three facts must be noted concerning the temporal-tectonic evolution of the entire East African Rift system:

a) The progression of the rifting from north to south. Therefore, the East African Rift system is older in the north and younger in the south.

b) The older parts of the system in the north were still active when rifting began in the south. The rifting and graben fracturing in the entire rift system is still continuing today.

c) A contemporaneity of all tectonic culminations can be seen throughout the entire rift system, for the taphrogenetic phases of the southern parts coincided with rejuvenations of the activity in the north.

Summarizing the scientific results in respect to the temporal-tectonic evolution of the East African Rift system, the following tectonic culminations or taphrogenetic phases can be noted:

Table 4 (Cf. fig. 2)

Age m. y.	Geological time	Event
	early Pleistocene	Graben faulting in the entire East African Rift system
2	end of Pliocene	Initial taphrogenetic phase in the Western Rift and the more southern parts of the Eastern Rift
2–3		Taphrogenetic phase in the Gregory Rift
2–3		Wonji fault belt in the southern Afar
3.5–4		Beginning oceanization in the northern Afar
5		Taphrogenetic phase in the entire Afar and in the Gregory Rift
11–9	end of Miocene	Taphrogenetic phase in the northern Afar, initial taphrogenetic phase (Chorora phase) on the Southeastern Escarpment and in the Gregory Rift, beginning of the pre-rift status in the Western Rift and the more southern parts of the Eastern Rift
25–23	Oligocene-Miocene boundary	Initial taphrogenetic phase in the northern Afar, beginning of the pre-rift status in the southern Afar and in the Gregory Rift
	Cretaceous-Tertiary boundary	Beginning of the pre-rift status in Ethiopia and in Yemen as well as in the region of the Red Sea

5. Zagros Orogen (Iranides)

The Zagros orogen comprises the mountain ranges in the western and southwestern parts of Iran and must be divided into several tectonic units (*Böckh* et al. 1929, *Schröder* 1944, *Stöcklin* 1968, *Pilger* 1971 and others). Neighbouring the Persian Gulf, there is the Outer Zagros. It is geologically a part of Arabia and has been covered with shelf sediments since the Cambrian. The Outer Zagros, to the northeast, borders abruptly against the important Zagros crush (thrust) zone (fig. 1). Here, the Inner Zagros fold belt is thrust southwest-ward over the Outer Zagros. It forms the suture line and subduction zone where Arabia contacted the Iran fold belt and Asia. To the northeast, it follows the Inner Zagros or the Zanandaj-Sirjan zone (or the Rezaiye-Esfandaghed orogenic belt, *Takin* 1972). Here, the orogenesis is older than that in the Outer Zagros and is characterized by folding, metamorphism, granitic intrusions and the ophiolite-radiolarite zones. There are also cores of Precambrian rocks. Northeast of the Inner Zagros, but west of the Lut block is a significant and particular magmato-tectonic unit, the Urmiah-

Dukhtar zone or central Iranian volcanic belt *(Gansser* 1960, *Falcon* 1967, *Förster* et al. 1972, *Vialon* et al. 1972 and others). It is characterized by very thick intrusive and extrusive magmatic rocks, mainly of intermediate chemical composition and mainly of Tertiary age. It can be traced for approximately 2,000 km and is probably connected with the subduction zone in Turkey to the west *(Förster* et al. 1972).

The Zagros orogen can be divided by temporal-tectonic aspects into four tectonic cycles:

1. *Mesozoic,* but excluding the latest part of the Upper Cretaceous: The Tethys geosyncline was spread between Asia and Arabia, the Lut block was probably an island within the Tethys (*Takin* 1972, *Dewey* et al. 1973). A first faulting event occurred east of the Lut in Triassic and Jurassic time (*Stöcklin* 1968, 1974). A first folding phase came into action in the Lut and its surroundings and in the Zanandaj-Sirjan zone at the Jurassic-Cretaceous boundary and the boundary between the Lower and Upper Cretaceous (*Böckh* et al. 1929, *Huckriede* et al. 1962, *Stöcklin* 1968, *Pilger* 1971). Then, there was an initial thermal metamorphism and intrusions of granite and gabbro (*Vialon* et al. 1972). The andesites and basalts in the Lut and probable Cretaceous seamounts to the west could be evidence of a first subduction around the Lut block (*Dewey* et al. 1973). It is also possible that crustal movements in the northeastern part of Iran occurred throughout the Zabzevar zone and continued into Afghanistan and the Tibetan plateau. A possible fossil subduction zone here could indicate the boundary of the Tethys and the northern continent of Asia (*Crawford* 1972, 1973, *Dewey* et al. 1973, *Stoneley* 1974).

   In the Upper Cretaceous, mainly in the Santonian and Lower Campanian, a culmination in the evolution of the Tethys occurred with the deposition of marine shales, radiolarites and thick ophiolites with chromite deposits. This evolution can be traced around the Lut block and along the entire Zagros crush zone continuing westward into the Taurus and eastward along the entire Indus suture line in the Himalayas, and the same formation can also be found in Oman. It is possible to speak of an eugeosynclinal status (*Gansser* 1960, 1964, 1966, *Morton* 1959, *Wilson* 1969, *Falcon* 1972) or a continental break-up and subsequent sea floor spreading (*Dewey* et al. 1973, *Glennie* et al. 1973). The evolution ended in the Upper Campanian, for shallow water limestones and flysch of Maastrichtian and Paleocene ages overlap the older deposits (*Allemann* & *Peters* 1972, *Stöcklin* 1974).

2. The *second cycle* of the tectonic evolution of this region began in Upper Campanian and Maastrichtian times and continued through the Paleocene until the deposition of the pre-Lutetian rocks. This is the Laramide period of this region (*Pilger* 1971). The tectonic events of this cycle occurred as a result of the first contact of Arabia and Asia and a first subduction of Arabia under the future Iran fold belt along the Zagros crush zone (*Wells* 1969, *Takin* 1972,

Förster et al. 1972, *Stöcklin* 1974). A subduction during this period is evident by the Amiran Formation in the Zagros which comprises Maastrichtian and Paleocene and contains abundant mica which must have come from Asia (*Falcon* 1967).

Contact and subduction during this period occurred together with a strong folding in the Inner Zagros and around the Lut block (*Pilger* 1971), a second stage of metamorphism and intrusions of granite and gabbro (*Vialon* et al. 1972).

Combined with the tectonic movements of the Laramide period, the coloured melange (*Gansser* 1964) was created by compression along the Zagros crush zone (*Gansser* 1964, 1966, *Stöcklin* 1968, 1974 and others). Probably, there were also subduction movements on the borders of the Lut block (*Takin* 1972). The coloured melange consists of slices and tectonic lenses of strongly disturbed ophiolites (with chromite ores), various sediments, flysch, micashists, blue shists, serpentinite, amphibolite, etc. A pelagic microfauna of late Cretaceous and early Tertiary ages has been found (*Davoudzadeh* 1972). In the region of the coloured melange, the Tethys geosyncline was totally compressed, leaving the melange as a fossil remnant. The coloured melange is overlain with an unconformity by Eocene flysch (*Wells* 1969, *Takin* 1972, *Vialon* et al. 1972. *Förster* et al. 1972, *Stöcklin* 1974), (see fig. 2).

The lenses and slices of the coloured melange, forming a tectonite, can be found along the entire suture line of the Taurides in Turkey, along the Zagros crush zone in Iran and along the Indus suture line north of the Himalayas. In Oman, there is not a subduction, but an obduction with a nappe of ophiolite caused by gravity sliding (*Lees* 1928, *Wilson* 1969, *Morton* 1959, *Allemann* & *Peters* 1972 and others).

3. The *third cycle* during the Eocene and Oligocene is a period of more or less tectonic quiescence, but with a continuation of the volcanic activity in the Urmiah-Dukhtar zone. There were small tectonic movements at the Eocene-Oligocene boundary.

4. The second period of intensified subduction of Arabia under the Iran fold belt began along the Zagros crush zone in the latest Oligocene and/or the early Miocene and continued until the present time (*Takin* 1972, *Förster* et al. 1972). The subduction was combined with a strong folding phase in the outer parts of the Inner Zagros fold belt (*Pilger* 1971). In the interior parts of Iran, older faults were reactivated. The Zanandaj-Sirjan zone continued with mainly intermediate volcanism and intrusions and was still a little active in the Quaternary. The Outer Zagros, west of the crush zone, had no folding nor unconformity from the Cambrian through the Miocene. It was folded only before and after the Pontian and then during the Pleistocene and Holocene (*Pilger* 1971).

Summarizing the tectonic and magmatic events of the Iran fold belt, the following tectonic culminations can be noted:

Table 5 (Cf. fig. 2)

Geological time	Tectonic culmination
Pre- and post-Pontian	Orogenetic phases of the Outer Zagros
Oligocene-Miocene boundary	Subduction of Arabia under Iran along the Zagros crush zone, orogenetic phase of the Inner Zagros along the Zagros crush zone
Pre-Lutetian, Paleocene, Upper Maastrichtian	First contact of Arabia and Iran along the Zagros crush zone, first subduction, strong orogenetic phase (Laramide phase) in the Inner Zagros, beginning of the andesitic volcanism along the Urmiah-Dukhtar zone
Lower Maastrichtian and Campanian	Ophiolite eruptions
Lower-Upper Cretaceous and Jurassic-Cretaceous boundaries	First folding phases around the Lut block

III. Tectonic culminations and the contemporaneity of tectonic activity in the described region

The Indian Ocean and the neighbouring areas to the west and north, have had a varied tectonic history. There are many different types of structures in the various areas and each has had its own evolutionary history. There was at no time complete quiescence but the tectonic activity has waxed and waned. At times this activity intensified to culminations. These culminations occurred repeatedly in all parts of the region and were the prominent feature of the tectonic evolution since all the various structures were created in such spasms. These structures include some produced by orogenetic phases, such as the folded Himalayas and the Iranian fold belt and, in contrast, others such as the East African Rift system, faulted in taphrogenetic phases by crustal extension. The Indian Ocean, the Red Sea and the Gulf of Aden came into being by sea floor spreading which showed accelerations and alterations in direction of drifting. The collision of Arabia and India with Asia, and the subsequent subduction under Asia, was an event by particular significance in the entire region.

Summarizing these facts, the different areas of the described region show very dissimilar tectonic structures with individual tectonic and magmatic evolutions. In spite of the dissimilar patterns in the different areas, all the structures have clear mechanical-tectonic relationships which have been described by many authors and need not be explained in this paper. It must also be emphasized that the different structures of the region also have temporal-tectonic relations which may point to uniform causes or even to a related evolution in temporal as well as in mechanical regard. These temporal-tectonic relationships can be shown by a contemporaneity of the tectonic culminations in the different areas.

In the following, we will identify all the tectonic culminations of the different areas and arrange them into a common time frame for the entire region. Thus, it will be possible to compare the timewise evolution of the different structures in order to obtain the periods of the contemporaneous tectonic events. We will begin with the period of the opening of the Indian Ocean, about 140 m. y. ago (fig. 2).

1. About 140 m. y. ago, Upper Jurassic or Jurassic-Cretaceous boundary: first splitting of the Indian Ocean, final separation of India from Africa and from Australia/Antarctica, first folding phase in the Iran fold belt, subduction west of Sumatra, deposition of Sylhet basalts on the Indian plate and Karroo basalts in East Africa.

2. About 100 m. y. ago, boundary between Lower and Upper Cretaceous: second folding phase in Iran, last Karroo basalt eruptions.

3. About 80 to 75 m. y. ago, Campanian and Lower Maastrichtian of Upper Cretaceous, corresponding to magnetic anomaly No. 32: strong acceleration of the northward drifting Indian plate, culmination in the evolution of the Tethys with sea floor spreading and eruption of ophiolites in the Bengal Sea, around the Lut block and around the areas of the later Indus suture line and the Zagros crush zone, first Trap volcanism in Yemen, southern Sinai and Somalia.

4. 70 m. y. ago, end of Cretaceous, corresponding to magnetic anomaly No. 30: the Indian and Arabian plates first contacted Asia along the entire Indus suture line and Zagros crush zone with beginning of subduction, first forming of the coloured melange along the mentioned suture resp. crush line or subduction zone and around the Lut block in Iran, first orogenetic phase in the Himalayas, first main folding phase in the Iran fold belt, beginning of the pre-rift status in the areas of the Red Sea, Gulf of Aden and northern Ethiopia with extrusion of Trap basalts. The period of acceleration of sea floor spreading and orogenetic movements lasted about 20 m. y.

5. 53 m. y. ago, corresponding to magnetic anomaly No. 21: the stronger tectonic movements ceased before the Lutetian in Lower Eocene, in the region of the later Bengal Sea probably a little later.

6. About 40 m. y. ago, Eocene-Oligocene boundary: beginning of sea floor spreading in the Red Sea, collision of the continental part of the Indian plate with Asia. The Indus trough, as the last remainder of the Tethys, disappeared in Upper Eocene. Second folding phase in the Himalayas. In the region of the southeastern Indian Ocean, the separation of Australia from Antarctica was finished (*Heirtzler* et al. 1968). There is an unconformity or a hiatus before the early Oligocene in the sediments of the Indian Ocean (*Pimm* & *Sclater* 1974, *Davies* et al. 1975).

7. 25 to 23 m. y. ago, end of Oligocene or Oligocene-Miocene boundary: main orogenetic phase in the Himalayas, along the crush zone in Iran and in the Taurides, strong subduction of India and Arabia under Asia along the Indus

suture line and the Zagros crush zone, unconformity within the Bengal Sea, subduction in the Andaman Sea and along the Sumatra trench, sea floor spreading in the Red Sea and the Gulf of Aden, initial taphrogenetic phase in northern Afar in Ethiopia, pre-rift status in Kenya.

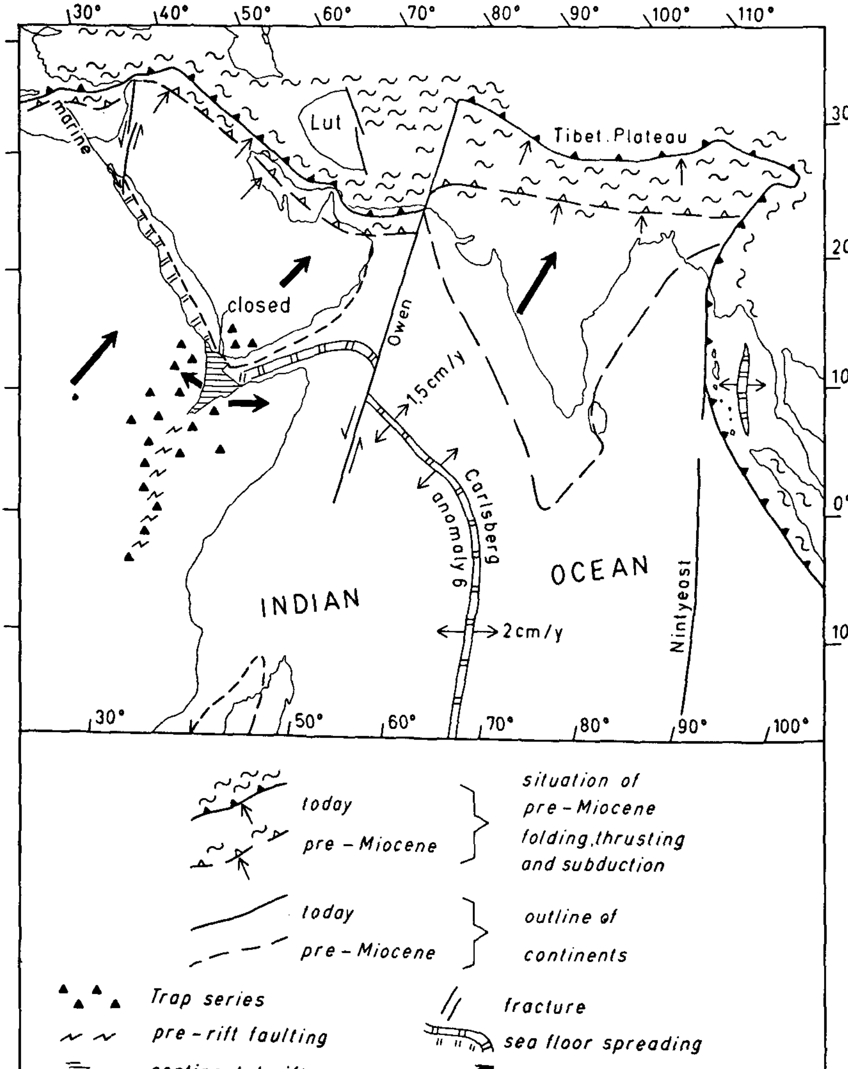

Fig. 5
The tectonic status of the Indian Ocean and neighbouring areas at the Oligocene-Miocene boundary, 25 to 23 m. y. ago. (From different authors.)

8. About 10 m. y. ago, Miocene-Pliocene boundary: third strong orogenetic phase in the Himalayas, first folding of the Outer Zagros in Iran, sea floor spreading in the Red Sea and the Gulf of Aden, taphrogenetic phases in the Afar depression in Ethiopia and the Gregory Rift in Kenya with strong volcanic activity.

9. End of Pliocene and during Pleistocene: additional orogenetic movements in the Himalayas and the Outer Zagros, taphrogenetic movements along the East African Rift system.

IV. Discussion: Contemporaneous tectonic events and global tectonics

In the preceeding chapters, the contemporaneity of the tectonic culminations during the evolution of the Indian Ocean and its neighbouring western and northern areas has been explained. Following are the dates of contemporaneous culminations in the different areas (see fig. 2):

about 3 to 1.5 m. y. ago, end of Pliocene to early Pleistocene;
about 10 m. y. ago, Miocene-Pliocene boundary;
25 to 23 m. y. ago, Oligocene-Miocene boundary;
about 40 m. y. ago, end of Eocene and Eocene-Oligocene boundary;
70 to 53 m. y. ago, Upper Maastrichtian, Paleocene, earliest part of Eocene;
85 to 75 m. y. ago, Upper Santonian, Campanian and Lower Maastrichtian of Upper Cretaceous;
about 140 m. y. ago, end of Jurassic and Jurassic-Cretaceous boundary.

These dates of synchronous tectonic events are tectonic culminations in the evolution of all described areas and cover an extensive region of the earth's surface. It is necessary to insert these facts into the ideas of the new global tectonics. For, the temporal-tectonic relations are a part of the global tectonics and such considerations will sureley ease the interpretation of sea floor spreading and plate tectonics.

The following features appear to be important:

1. The culminations of the tectonic evolution were often of relatively short duration of only a few million years, e. g. that on the Oligocene-Miocene boundary. But, some other tectonic culminations also showed a longer period of tectonic activity or a longer tectogenetic phase, such as the approximately 20 m. y. period of tectonic movements at the Cretaceous-Tertiary boundary. However in most all cases, the tectonic culminations began quite abruptly and can be sharply defined in time.

2. The mentioned contemporaneous tectonic activities produced very different structures. They occurred contemporaneously in oceanic and in continental crust, in crust growing due to sea floor spreading and in crust being consumed by subduction. Included are areas of folding and thrusting as well as areas of faulting.

From this pattern of varied and contemporaneous tectonic movements near the earth's surface, it must be deduced that the driving force has its origin in the earth's mantle or in even deeper parts of the earth.

3. The idea of temporal coherences of tectonic events has been dealt with by different authors. As early as the middle of the 19th century, *Beaumont* (1852) knew that the building of the mountains occurred in stages. Later, many geologists of different countries pointed to particular periods of tectonic activity and to a contemporaneity of tectonic events. A first synopsis of the contemporaneity of tectonic events was given by *Stille* (1924, 1940). He emphasized that 1) orogenetic phases occured episodically during the earth's evolution and were separated by long unorogenetic periods; 2) the orogenetic phases were of (geologically) short duration; 3) single orogenetic phases occurred contemporaneously in different parts of the earth's (continental) crust.

There have been many discussions about the hypothesis of *Stille* (1924, 1940, etc.), e. g. about the (too) short duration and the (too exact) contemporaneity of the orogenetic phases or even if there were relatively short orogenetic phases at

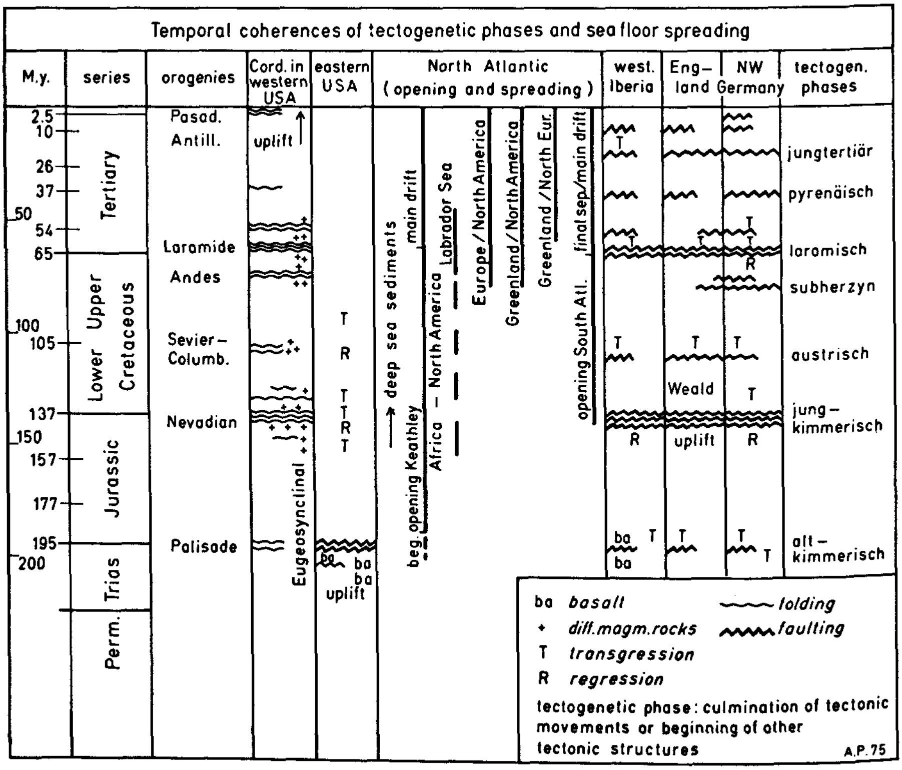

Fig. 6
The main tectonic events of North America and Europe and the opening of the North Atlantic since 200 m. y. ago. For comparison with fig. 2.

all. However, the fundamental idea was, often with variations, accepted by many geologists. In any case, it must be emphasized that the idea of the temporality and the (possible) contemporaneity of the tectonic movements originated and was developed by *Stille* to a broad and spectacular hypothesis.

4. On a global scale, although some authors have already made contributions concerning temporal coherences of the tectonics (see chapter I), there probably is not yet sufficient material to integrate the temporal-tectonic ideas fully into the hypothesis of the new global tectonics. However, there are significant correspondences between the tectonic culminations of the described region and the tectonic events in other parts of the earth. The break-up of the Indian Ocean and the beginning of the northward wandering of the Indian plate at the boundary between the Jurassic and the Cretaceous corresponded in temporal regard with the Nevadian orogeny of the Sierra Nevada in North America. In this region, the culmination of folding and granitic magmatism occurred at the end of Jurrassic (*Kummel* 1970, p. 271, 275). In western Germany, there were tectonic (saxonic) movements in the upper parts of the Upper Jurassic and the lowest part of the Lower Cretaceous which *Stille* (1924) called the „young-kimmerian phase". There also were tectonic movements, for instance in respect to the opening of the northern Atlantic, at the Jurassic-Cretaceous boundary (*Hallam* 1971, *Coney* 1971 and others) (fig. 6).

The uppermost part of the Upper Cretaceous and the Paleocene, where the region of the Indian Ocean and its neighbouring areas showed a strong tectonic activity of a different type, was a time of wide-spread and strong tectonic movements of the earth's crust. „Not since Precambrian time had there been such a major mountain-building epoch in North America ... Folding, faulting, and overthrusting on a gigantic scale formed the present Rocky Mountain system ... and the Andes of western South America ... This phase of deformation was named the Laramide orogeny" (*Kummel* 1970, p. 287; see also *Stille* 1940). At the same time, or 60 to 65 m. y. ago, the northern part of the Atlantic between Greenland and Scandinavia began to open. There were also important tectonic movements in England, in the saxonian area of Germany and in the Alps (fig. 6). It must be emphasized that the Cretaceous-Tertiary boundary is one of the most important periods of strong tectonic movements of the earth.

5. It is very conspicuous that the time table of the magnetic anomaly pattern shows some correspondences with the table of the tectonic phases (fig. 7). There was a long period of normal polarity during the Upper Cretaceous. With the beginning of the tectonically active period of the Laramide orogeny in the uppermost part of Cretaceous, a frequent change of normal and reversed polarity came into being. The polarities also changed rapidly, at times corresponding with the tectonic culminations at the end of Eocene and on Eocene-Oligocene and Oligocene-Miocene boundaries.

6. Our knowledge is not sufficient enough to give an exact statement of the contemporaneous tectonic events of such a huge region as described in this paper

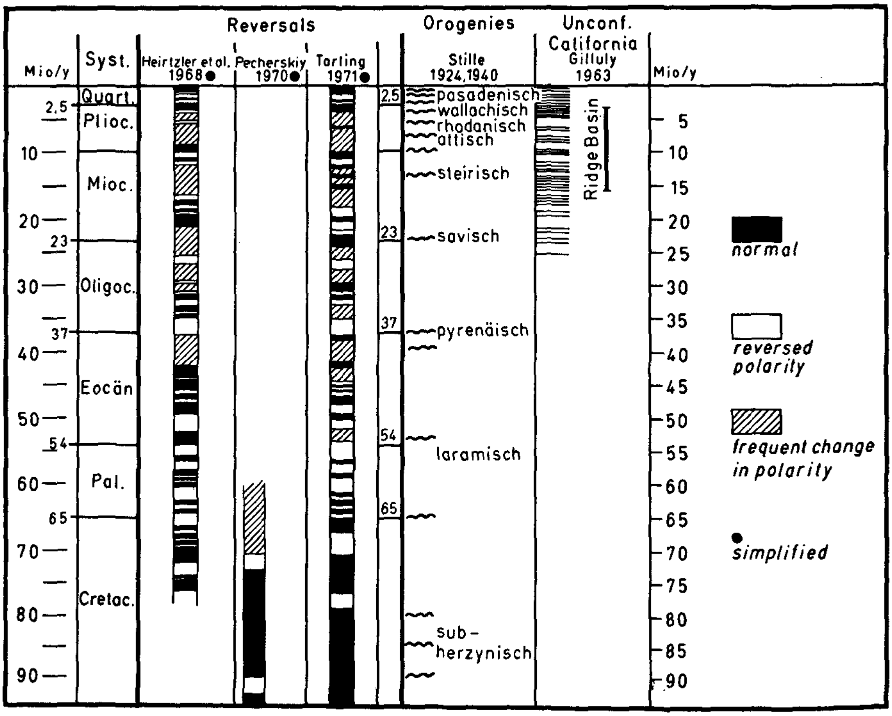

Fig. 7

Palaeomagnetic pattern and the orogenetic phases from *Stille* (1924, 1940). *Gilluly* (1963) did not correspond with *Stille's* orogenetic phases. He found in California indications of numerous and very frequently repeated small tectonic movements. The long period of normal polarity ended with the period of tectonic activity at the Cretaceous-Tertiary boundary.

or over the entire earth's crust. However, all information points to the supposition that physical and chemical forces of the earth's interior do influence decisively the tectonic and magmatic processes of the upper part of the mantle and crust to drive the global tectonics. But, there are different opinions concerning the temporal relations of the movements of the plates in the continental and the oceanic crust (*Wunderlich* 1966, *Dewey* & *Bird* 1970, *Coney* 1971, *Hallam* 1971, *Vogt* & *Johnson* 1971, *Rutland* 1971, *Sykes* & *Sbar* 1973, *Schwan* 1974, *Meyer* 1975, *Schönenberg* 1975 and others).

The predominant opinion of movements within the earth's interior, first given by *Holmes* (1929), suggests a mechanism of convection currents (or streams) within the mantle. This opinion was accepted by different scientists and fits the present science. Only, there are different conceptions concerning the kind of movements of the convection streams. Probably they rise vertically below the oceanic and continental ridges and descend below the fold belts. Between these prominent courses they run horizontally. Possibly the convection streams are not entirely linear but show turbulences (*Wunderlich* 1966). It may be suggested that interactions between different convection currents produce turbulence, and that this turbulence is particularly effective in causing contemporaneous tectonic deformations of the lithosphere.

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